EFFECT OF QUENCHING MEDIA AND SPECIMEN SIZE ON HARDNESS OF AISI 1060 CARBON STEEL

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الخلاصة

الغرض من المعالجة الحرارية للصلب الكربوني هو تحسين خواصه ومن ضمنها الصلابة والصلادة وتعتمد المعالجة الحرارية لصلب ما على عدة عوامل مثل درجة الحرارة وزمن التسخين، نوع ووسط التبريد وكذلك شكل وحجم الجزء المعالج.

يوجد الكثير من أوساط التبريد المستخدمة في عمليات المعالجة الحرارية مثل الماء، الزيت والهواء وغيرها. وعليه فإن اختيار نوع المبرِد يعتمد على معدل التبريد المطلوب والذي بدوره يتأثر بسمك وشكل الشغلة. من وجهة نظر مبدأ الانتقال الحراري فإن النسبة بين المساحة السطحية إلى حجم جزء ما يعتبر من أهم العوامل لتحديد سلوك الانتقال الحراري بحيث عندما تزداد هذه النسبة فإن معدل التبريد يزداد مما يؤدي الى زيادة الصلادة.

لذا فإن الهدف من هده الدراسة هو البحث عن تأثير بعض المعالجات الحرارية في الصلادة السطحية وكذا الصلادة الداخلية لعدد من العينات الدائرية مختلفة الأقطار من الصلب الكربوني AISI 1060 وذلك بتسخينها عند درجة حرارة 825°C لمدة ساعة ثم تبريد بعضها مباشرة في الماء العادي والبعض الاخر في زيت المحرك المستعمل وأيضا في الهواء الطلق وفي الفرن مغلقا بعد قطع التيار الكهربائي عليه.

أوضحت نتائج هذا البحث أن الصلادة السطحية وكذلك الصلادة الداخلية ارتفعتا وذلك بزيادة مقدرة وسط التبريد (زيادة معدل التبريد). أيضا أظهرت النتائج ان الاختلاف بين الصلادة السطحية والصلادة داخل مادة العينة (القلب) بسيط لجميع وسائط التبريد. من ناحية أخرى فقد بينت النتائج انه لا قطر العينة ولا النسبة بين مساحة سطحها وحجمها كانا لهما تأثير ملحوظ لا على الصلادة السطحية ولا على الصلادة الداخلية.

ABSTRACT

The purpose of steel heat treatments is mainly to improve its properties including strength and hardness. The heat treatment of a particular steel depends on many factors such as temperature and time, type of coolant and the shape and size of the part.

There are many commonly used cooling media in carrying out heat treatment such as water, oil,…ets. The selection of coolant depends on the desired cooling rate which in turn relevant to the section thickness and shape. From heat transfer point of view, samples surface to volume ratio is a key factor in assessing its heat transfer behavior. When this ratio increases, the associated cooling rate will be higher and consequently a higher hardness in the entire sample can be attained.

The objective of this study is to investigate the influence of various heat treatments on the surface and interior hardness of different sized round specimens of plain carbon AISI 1060 steel. The steel samples were austenitized at 825°C for one hour soaking time and quenched in various media, particularly tap water, used engine oil, dry air and furnace.

The results indicate that both surface hardness and cross-section hardness are increased with increasing the severity of quench irrespective of specimen size. Furthermore, the results of the present work showed that almost no variations between the hardness at the surface and the hardness at the core of the specimens. On the other hand, neither the specimen diameter nor the surface area to the volume ratio were found to have a strong influence on the behavior of the obtained hardness either at the surface or at the core of heat-treated steel samples.

Key words: AISI1060 steel, heat treatments, hardness, microstructure.

1. INTRODUCTION

The microstructure of a given steel can be altered by heating it at a different temperature and time, then allowing it to cool at suitable rate. The mechanical properties of steels are strongly connected to their microstructure obtained after heat treatments that are generally performed in order to achieve a good hardness and / or tensile strength with sufficient ductility. The effectiveness of heat treatment depends on many factors including:

- Heating temperature and time.
- Cooling medium.
- Chemical composition of steel.
- Geometry of the work piece.

In practice, cooling process is usually conducted in media that could be liquid (water, oil, …etc), dry or compressed air, gases like Ar, H2, N2, He, spry mixture (gas + liquid).

The cooling rate (°C/S), therefor is a fundamental factor in carrying out of all heat treatments. The cooling rate of specimen depends on the heat energy extraction in such that during quenching, heat energy must be transferred to the surface before it can be dissipated to the quenching medium. As a consequence, the cooling rate within and throughout the interior of a steel structure varies with position and depends on the characteristics of the quenching medium as well as the specimen size and shape.

According to the above, if the actual cooling rate of a particular steel exceeds a cooling rate known as a critical cooling rate (CCR), the predominant phase in the microstructure of this steel will be martensite. If the cooling rate is slower than the CCR, the work piece will not completely be hardened. The greater the difference between the actual cooling rate and CCR, the lower hardness will be the transformation products.

As far as specimen shape is concerned, the heat energy is removed from the surface of the specimen, as a result the cooling rate depends upon the surface to volume ratio. By increasing this ratio, the associated cooling rate will be higher and consequently a higher hardness in the entire sample can be achieved.

The calculation shows that, the surface area to the volume ratio is inversely proportional to diameter in such that within a fixed quenching medium, a relatively large piece will be cooled more slowly than small piece. On the other hand, if cooling curves are drawn at a different specimen location, for example, at the surface, at the midway and at the core of the cross-section of two bars differ in their diameters and have the same Thickness (height) and being quenched in the same medium, the cooling curves of such sites of the smaller bar will be much closer to each other. Indicating that a limited variation between the hardness values at surface, midway and center is to be expected compared to the rod of larger diameter.

It is to be mentioned that as many as researchers have been conducted investigating the mechanical properties including hardness of various heat-treated specimens mostly have the same shape and size. Meanwhile, some other researchers carried out such investigations on round samples that are extremely differ in thickness as well as in diameters, hence the specimens have a higher variation in the surface area to volume ratio.

Accordingly, the aim of the present work is to study the behavior of the hardness at the surface and the interior of AISI 1060 round samples variously heat treated. Three specimen diameters are employed that have a relatively small difference in between, mainly 48mm, 43mm and 38mm. Moreover, this work includes studying the hardness of some specimens that have fixed surface area to volume ratio and compared to those specimens slightly differ in this ratio.

2. EXPERIMENTAL WORK

2.1 MATERIAL

Unalloyed medium carbon engineering steel (AISI 1060) is used in this work. This steel was supplied from HALDEN Special Steel Company in the form of hot forged round bar of chemical composition shown in table 1.

Table 1: Chemical composition of AISI 1060 steel.

Element	C	Mn	P	S	Si	Cr	Mo	Cu	Sn
Wt. %	0.59	0.72	0.01	0.001	0.22	0.09	0.01	0.13	0.01

2.2 SPECIMEN PREPARATION

Samples of three different diameters; 45, 43 and 38 mm were sectioned from the steel rods. The samples were divided into two batches as follows:

Batch 1: In which the thickness was kept the same for all specimen diameters

of 10 mm.

Batch2: In which the thickness is varied in such that the surface area to volume ratio remained constant using the fallowing formula:

$2\pi rt + 2\pi r^2 / \pi r^2.t$ = constant. In which ($2\pi rt$) term represents the lateral surface area and ($2\pi r^2$) represents the surface area of the base and top of a round specimen whereas the term ($\pi r^2.t$) is the specimen volume where:

r: specimen radius.

t: Thickness.

The above equation could be reduced to $2/r + 2/t$ = constant.

The thickness of specimen of large diameter (48mm) was arbitrary chosen to be 10mm. Therefore, the constant equals 0.2833 and accordingly the other two thicknesses were calculated depending on the above equation ($2/r + 2/t = 0.2833$) and found to be 10.511 mm and 11.233 mm for 43mm and 38mm specimen diameters respectively.

2.3 HEAT TREATMENTS

The heat treatment cycle includes austenitizing the steel samples at a temperature of 825°C as recommended by ASM Hand Book [1] in a SIB electrical furnace (Italian made) of 1100°C maximum heating temperature. The temperature of 825°C thought to be capable enough to achieve a fully austenitic structure for such type of steel. The steel specimens were held at (825°C) for one hour, then after they were immediately cooled down to room temperature in

various media, mainly tap water, used oil of car engine, normal air and in furnace after being shut down.

According to the utilized heat temperature, the samples were assigned with the fallowing codes, (WQ1, WQ2, OQ1, OQ2, N1, N2, A1 and A2) in which the litters W, Q, O, N and A are stand for Water, Quench, Oil, Normalizing and Annealing respectively and the numbers 1 and 2 refers to batch 1 and batch 2 as mentioned before.

Six specimens were used for each heat treatment i.e. (one specimen x three diameters x two batches). Therefore, the total number of specimens are 24 (six specimens x four media).

2.4 HARDNESS MEASURMENTS

Before measuring the hardness, the specimens were thoroughly cleaned by using soft wet emery paper to remove any scales or oxides that formed during heating which may affect the results.

2.4.1 SURFACE HARDNESS MEASURMENTS

Erast Hardness Tester type (NR3D) was used to measure the hardness of all heat treated steel samples. Rockwell hardness (scale C) used for water and oil quench samples, whereas Brinell hardness was utilized for normalized and full annealed one. All hardness readings were tabulated in Brinell hardness using a conversion table. About eight readings were randomly taken on various surface locations and the average were reported.

2.4.2 CROSS SECTION HARDNESS MEASURMENTS

The quenched steel samples as well as the normalized one were sectioned in to two equal halves through the thickness using wire cutting under cooling aiming to measure the profile hardness. The cross-section hardness was made from the edge of specimen along to its center in such that the measurements were about 3mm in apart from each edge.

2.5 METALLUGRAPHIC INSPECTION

Various specimens represent different heat treatments involved in this work were metallographically prepared including grinding with silicon wet emery papers down to 1200 grit and polished with alumina powder slurry until a flat mirror like surface was obtained. The samples were then etched with 2% nital and being microscopically examined by (Nikon) optical microscope at different locations either at the surface or at the interior of test sample.

3. RESULTS AND DISCUSSION

3.1 SURFACE HARDNESS

3.1.1 EFFECT OF COOLING MEDIA

Table 2 summarized the average surface hardness of approximately eight readings for each heat-treated specimen. From this table one can realize that the surface hardness is increased with

severity of coolant for all specimens (batch1and batch2). Quenching in water gave the highest hardness being more than two times of oil quenching and even more than three times of either air cooling or furnace cooling. Meanwhile, the variations between the surface hardness of specimens cooled in oil, air and furnace are relatively smaller. On the other hand, the differences between the hardness values of batch1 and batch2 are almost negligible for all heat treatments and specimen diameters as predicted in table 2 and illustrated in Figure 1 for 48mm specimen diameter as an example even though, in some cases being equal. In this aspect the slight variation between the thicknesses seems to have almost no influence on the obtained results.

The above results may be discussed in the light of continuous cooling transformation curve CCT [2] (Figure 2). The water quenched specimens supposed to be rapidly cooled with a cooling rate that was faster than a cooling rate known as a critical cooling rate (CCR) which equals approximately 160°C/S as estimated from the CCT curve. This cooling rate is capable enough to transform austenite phase to a hard phase called martensite so that no pearlite can able to form. On the other hand, the martensite starts temperature (Ms) as well as (Mf) [3] are greater than the room temperature which allows almost austenite to transform to martensite. The above result could be confirmed by the microstructure shown in figure (3a) which consists of almost martensite phase with retained austenite.

Table 2: Brinell surface hardness results of various heat treated steel samples.

Specimen code	Average Hardness (HB)		
	d= 48mm	d= 43mm	d=38mm
WQ1	665	670	684
WQ2	670	670	698
OQ1	294	311	341
OQ2	284	313	341
NQ1	238	244	257
NQ2	231	236	249
A1	209	214	214
A2	200	209	206

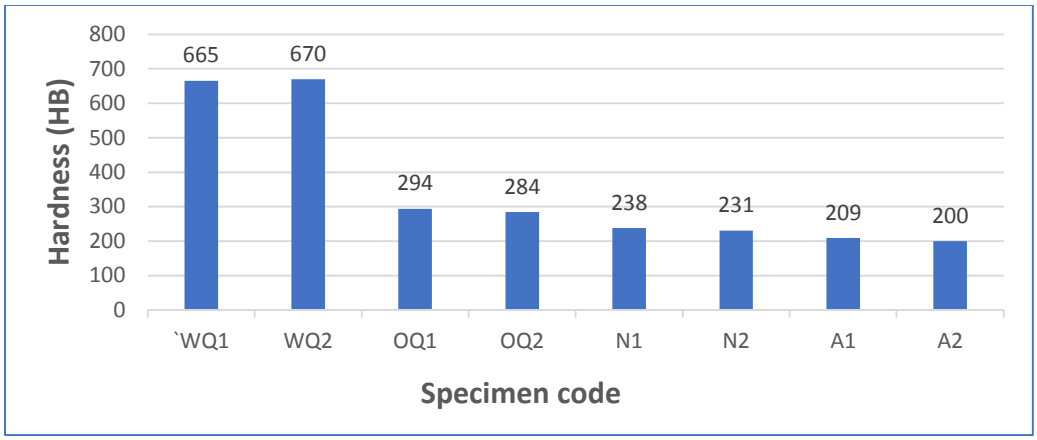

Figure 1: Average surface hardness of all heat treated 48mm specimens diameter.

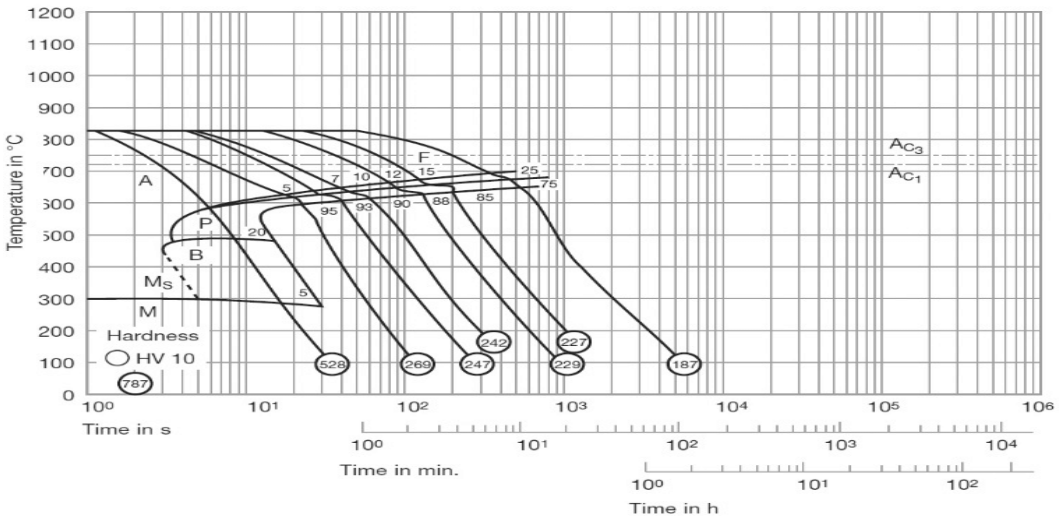

Figure 2: continuous cooling transformation curve of AISI 1060 Steel.[2]

Figure 3-a: Martensite needles in

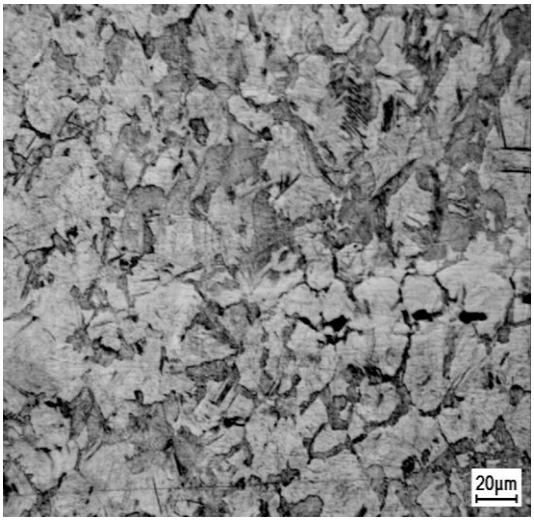

Figure 3-b: Matrix of martensite (light)

retained austenite matrix with pearlite (grey). Some bainite and dissolved carbides are also visible.

Figure 3-c: Fine lameller pearlite (dark) and some ferrite (white) being formed on the original grain boundaries of austenite.

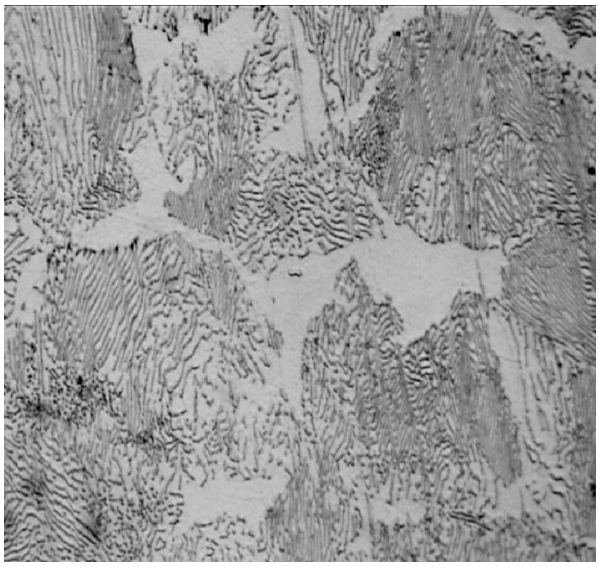

Figure 3-d: Colonies of coarse pearlite (dark) and some ferrite (white) trapped between pearlite colonies.

Figure 3: Optical micrographs of steel specimens cooled in (a) water, (b) used engine oil, (c) air and (d) furnace (400x).

As for the specimens quenched in oil, their hardness was noticed to sharply drop compared to water quenched samples. Quenching power of oil is far less drastic than that of water, this makes sense because water flows more freely than oil which allows heat to transfer in water faster than in oil, that is also physically more viscous than water. The cooling rate therefore is considerably slow. Such intermediate cooling rate lets the formation of a pearlite phase to take place and hence the microstructure of these samples would be a mixture of martensite and pearlite as shown in figure (3b). As a pearlite phase is softer than the martensite phase i.e. HV of martensite is approximately 870 compared to that of pearlite HV 250. Therefore, the hardness of oil quench steel is substantially lowered. Cooling rates encountered in either normalizing or full annealing heat treatments are thought to be too slow in such that the austenite to martensite reaction is no longer exist. Alternatively, the structure of steel will normally consist of pearlite and free ferrite (Figure 3c and d) that are of lower hardness (HV of ferrite is = 81). Nevertheless, the variation between the hardness of normalized samples and full annealed once is partially attributed to the texture of the formed pearlite.

Normalizing produces a finer and more abundant pearlite structure than annealing. The finer the pearlite is the harder and stronger it is. Furter more, the weight percentage of free ferrite in the full annealed samples as estimated by the lever rule was found to equal ~22wt% and the remaining phase is pearlite equal ~78%. The weight percentage of free ferrite in normalized samples though to be less than 10 wt.% as estimated from (Figure 3-c) which in turn corporates in raising the hardness of normalized steel compared to the annealed one, as the hardness of pearlite is more than three times that of ferrite as mentioned earlier. The above results are in a good agreement with some other previous results, see for example, Dnan Colik [4] who found that the hardness HV of 1060 carbon steel quenched in water, air cooled, and furnace cooled are 610, 203 and 167 respectively.

3.1.2 EFFECT OF SPECIMEN SIZE

As for specimen shape is concerned, the rate of cooling depends on the ratio of surface area to the volume of the specimen. The larger this ratio, the more rapid will be the cooling rate and consequently the deeper the hardening effect [5].

The surface macro-hardness results (Table 2) indicate that, decreasing specimen's diameter mostly accompanied with an increase in hardness irrespective of specimen's batch. However, the increase in surface hardness with reducing the specimen's diameter (Figure 4) was noticed to be less pronounced as the quenching

power is lowered. Lowering the severity of quench allows sufficient time for the specimen to cool. As a result, the cooling rate will be less sensitive to the specimen's size, producing nearest surface hardness.

Regarding to the surface area to volume ratio, it should not have any effect on the hardness of batch2 specimens, hence it was kept constant (0.2833) as well as the specimens of 48mm in diameter of batch1. Moreover, this ratio (2/r + 2/t) of batch1 specimens was calculated to be 0.2833,0.2930 and 0.3053 for 48mm, 43mm and 38 mm diameters respectively. The variation in between such constants were 9.7×10^{-3}, 12.3×10^{-3} and 22×10^{-3}. This implies that such lower discrepancies values appeared to be less able to develop a significant influence on the measured hardness. Rather the mass of the specimens seems to have such a slight effect in this behavior. The masses of batch1 specimens are 169g, 143g and 120g the equivalent masses of batch2 specimens are141g, 110g and 86g for 48mm, 43mm and 38mm respectively. Accordingly, it can be observed that light specimens mostly possess relatively higher hardness. However, if the surface area to volume ratio of constant thickness specimens desired to have crucial role in obtaining substantial differences on surface hardness, the variation between the sample diameters need to be much higher. For example, the surface hardness for oil quenched cylinders of 1060 steel were 59, 34.5 and 29 HRC for 0.5, 1.2 and 4 inch specimen diameter [6]. The surface hardness of 1045 round specimen of 2 inch in diameter quenched in water was 41 HRC whereas that of 5 inch in diameter was only 24 HRC [7].

Concerning to the specimen size, it may be postulated that, if the diameter of the steel piece is made too long and a given surface hardness is obtained by quenching it in water. A nearly the same surface hardness would have been obtained if the same steel piece has been cooled in the furnace. In such condition, the amount of heat to be removed is so large compared with surface area available that water quench is ineffective. The above postulation clearly demonstrates the striking influence of specimen size on the hardness of the heat treatable steel.

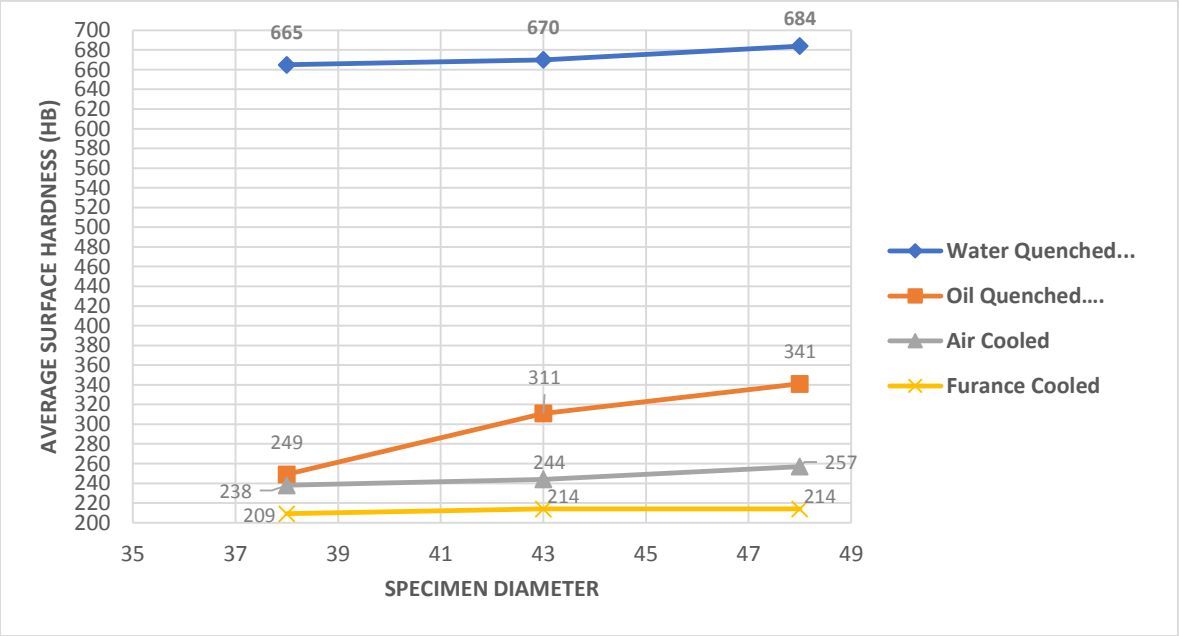

Figure 4: Variation of hardness with specimen's diameter (batch1)

3.2 CROSS SECTION HARDNESS MEASURMENTS

Knowing that the surface of the piece is in actual contact with quenching medium, so that it cools most rapidly than the interior. Figure (5) shows that at any instant (t) there will be a considerable temperature difference $T_3 > T_2 > T$□. Consequently, the cooling rates at the surface, midway and at the center will vary significantly as well as in the entire section of the sample. The variation in the cooling rate is directly proportional to the specimen size. If such variation in the cooling rate exists across the diameter of the sample, it is to be anticipated that variations in hardness would be evident [7].

According to the above, the hardness profiles across the diameter of some specimens quenched in water, oil and air were measured. The specimens cooled in furnace were omitted as long as there is sufficient time for the heat to be homogenized between the surface of the specimen and its interior, hence the cooling rates over the entire specimen would be mostly the same.

Therefore, no variation between the hardness across the specimen is to be anticipated for such specimens.

As mentioned previously, the difference between the diameters as well as the thickness of the used specimens are too small to have a substantial influence on the obtained results. In this aspect, it was found that the hardness profile does not fallow the expected trend in which the hardness should gradually decrease as we move from the surface to the core of the piece. Rather, the hardness values were having a random distribution over the sample's cross-section. Actually, most readings were nearly equal to the surface hardness. This implies that the cooling rate seems to be almost the same in the entire structure. The above tendency appears to be unusual and questionable, hence further investigation need to be carried out to explain it. For the air quenched steels, the above behavior may be explained in that the heat dissipated very slowly from the sample surface to the quenching medium (free convection). Hence the austenite to pearlite transformation should develop in the entire cross-section of the sample with small amount of free ferrite. The hardness of such samples either at the surface or at the cross-section demonstrates the above explanation which ranged between HB238 – HB257 that is approximately equivalent to the prementioned pearlite hardness (HV 250). Similar results were observed by Shan [8] who found that the hardness of oil quenched 38mm diameter spring steel specimen was 50 HRC at the core and 57 HRC at the surface.

Ali and Majid [9] have investigated a cylindrical and square AISI 4140 specimens shapes of various diameters. They found that the HRC hardness along the cross-section of the specimen did not vary much either for the smaller specimens or larger once irrespective of quenching media which partially consistent with the present study.

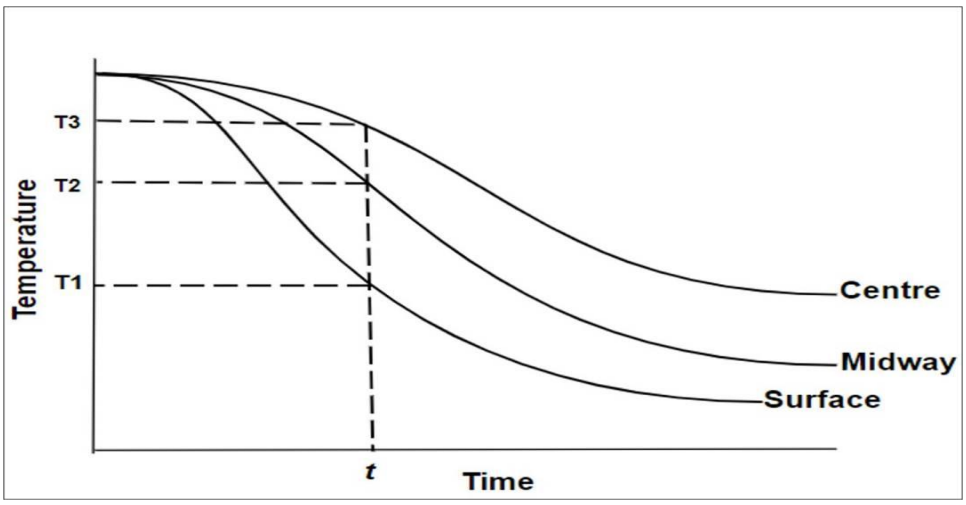

Figure5: Schematic representation of cooling rates at surface,

midway and center of round specimens.

It is worth mentioned that the hardness profile of heat-treated steel should be considerably varied with rod diameter due to the higher variation in the cooling rate associated with longer rod diameters compared to the smaller once. The variation in the specimen diameter may let the hardness at the core of smaller rod of particular steel to be even equal to the surface hardness of a larger diameter rod of the same height and received the same heat treatment as schematically shown in Figure (6).

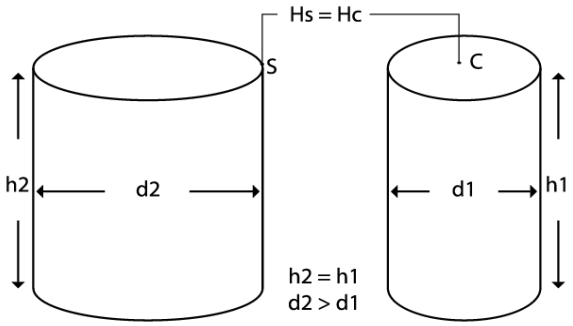

Figure (6): Schematic representation of changing hardness with rod diameter

Unlikely, such behavior was not observed among the three specimen's diameters used in the current work. That is may mainly be attributed to the limited differences between the employed diameters as stated previously.

CONCLUSIONS

The present investigation deals with the dependence of hardness property on the cooling rate and on the specimen dimensions of AISI 1060 carbon steel subjected to various heat treatments. The results of this study presented that, the surface hardness and the interior hardness are found to increase with the severity of quench irrespective of specimen size. More ever, the increase in the hardness was attributed to the increase in the martensite phase of water quenched and oil quenched steel samples, whereas the pearlite phase of the normalized and full annealed steels was considered to be responsible of such increase in the hardness.

On the other hand, it may be concluded that, the limited variation in the diameter of the tested steel samples as well as the lower surface area to volume ratio were found to have a decisive influence on either the surface hardness or the cross-section hardness.

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RERERENCES

1- Metals hand book, American Society for Metals, Metals Park, Oho, 1985, pp28.13

2- Atlas of isothermal transformation diagram US steel corporation.

3- R. Reed – Hill and R. Abbaschian, "Physical Metallurgy Principles", PWS Publishing, Third Edition, 1994, pp 654

4 - Adan Calik "Effect of Cooling Rate on Hardness and Microstructure of AISI1020, 1040 and AISI 1060 Steels" International Journal of Physical Science, Vol. 4 (a), 2009, pp 514.

5- W. Smith and J. Hashemi "Foundation of Materials Science and Engineering", Mcgraw – Hill Publishing, 2006.

6- William D. Callister, Jr, "Materials Science and Engineering: an Introduction", John Wiley & Sons, Jnt, Seventh Edition, 2007, pp 400.

7- Sidney H. Avner "Introduction to Physical Metallurgy", Mcgraw – Hill Publishing, Second Edition, pp 209, 1964.

8- M. Shan. S. Thu and K. Thi "Effect of Heat Treatment on Mechanical Properties of Spring Steel", Journal of Metals, Materials and Minerals, Vol.18 No.2, 2008. pp 191.

9- Ali Rafa Altaweel asn Majid Tolouei – Rad, "Effect of Quenching Media, Specimen Size and Shape on The Hardenability of AISI 4140 Steel", Emirates Journal for Engineering Research, 19 (2), 2014, pp 33.